COST ANALYSIS OF ATMOSPHERE MONITORING SYSTEMS

CONTRACT NO. NAS8-28377

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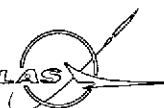
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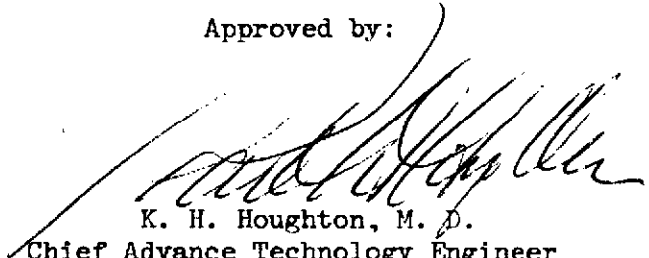
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Section 1

INTRODUCTION AND SUMMARY

1.0 INTRODUCTION

The ability to estimate approximate costs of new programs has been
found to be of great value to cognizant agencies embarking on new technology
programs. The design and development of equipment for flight use in earth-
orbital programs have also been found to proceed through a logical progression
from bench testing on breadboard units, fabrication and evaluation of prototype
equipment, redesign to meet flight imposed requirements, qualification
testing, and incorporation into a flight-ready system. Each of these steps
is intended to produce the basic design information necessary to progress
to the next step. The cost of each step is normally substantially less than
that of the following step.

A methodology has been developed and is presented in this report to
predict the relevant contributions of the more intangible cost elements
encountered in the development of flight qualified hardware based on an
extrapolation of past hardware development experience. Major items of
costs within life support subsystems have been identified and related to
physical and/or performance criteria. Cost and performance data from Gemini,
Skylab, and other aerospace and biotechnology programs were analyzed to
identify major cost elements required to establish cost estimating relation-
ships for advanced life support subsystems.

This report deals with the cost analysis of two leading atmosphere
monitoring systems, namely the Mass Spectrometer and the Gas Chromatograph.
A summary of the approach used in developing the cost estimating techniques
is presented in the following paragraphs. Included are the cost estimating
techniques, the development of cost estimating relationships and the atmosphere
monitoring system cost estimates.

1.1 APPROACH

The two atmosphere monitoring systems have been quantitatively evaluated.
System characteristics, including gas flows through the instruments and

and performance and physical criteria were also analyzed. Additionally, the status of development of each of the two systems considered and the required advance technology efforts required to bring pre-prototype hardware to an operational status were defined. Intimate knowledge of the operations, development status, and the capabilities of systems to meet space mission requirements were found to be essential in establishing the cost estimating relationships for advanced systems.

1.2 COST ESTIMATING TECHNIQUES

The atmosphere monitoring systems cost estimating techniques were developed by 1) identifying the physical and performance characteristics of each of the system components: 2) establishing or utilizing existing cost estimating relationships (CER's) for each of the components considered; and 3) the summation of equations for respective system components to establish the total system cost estimation. The U. S. Bureau of Standards Consumer Price Index was used to account for inflation and economic escalation.

1.3 DEVELOPMENT OF COST ESTIMATING RELATIONSHIPS

The methodology used in the development of CER's is as follows:

1. The components were analyzed to determine which physical or performance characteristics might prove useful as predictive variables.

2. Costs were arrayed graphically against the candidate variables either singly or grouped. The most promising of these arrays were selected on the basis of a subjective analysis which considers the appropriateness of the variables, the form and slope of the curves, and the relative aspects of the component costs.

1.4 ATMOSPHERE MONITORING SYSTEM COST ESTIMATES

A system schematic was prepared for each of the two atmosphere monitoring systems considered. System description, performance and physical characteristics were also given. The physical and performance parameters were identified for

use in formulating the cost estimating relationships. Recurring CER's were then developed and computed for each of the system subassemblies and summed up to obtain the integrated system recurring cost estimates. The system's non-recurring CER's were computed on an integrated system basis. The major influencing parameters for the non-recurring CER's were found to be the number of mechanical component types and the number of electronic printed circuit boards in the system.

1.5 ATMOSPHERE MONITORING PROTOTYPE COST ESTIMATES

A methodology has been developed to provide cost estimates of the following types of prototypes:

1. Low=fidelity prototypes: Made of flight-type, but not flight weight hardware, these prototypes are developed to prove operational performance when integrated with an operational life support system.

2. High-fidelity prototypes: these are flight-qualifiable units which have not undergone flight testing. Cost estimates of low-and high-fidelity prototypes were found to be approximately 5 and 10.2% of qualified subsystem costs, respectively.

However, the state of development of the types of Gas Chromatograph and Mass Spectrometers considered in this study is already more advanced than that of a low-fideltity prototype. Consequently, low-fidelity prototypes, which have been considered for other life support systems, were not presented in this report.

Section 2

COST ESTIMATING TECHNIQUES

The methodology used in establishing cost estimating techniques for life support systems is based on 1) the identification of the physical and performance characteristics of each of the system components, 2) establishing or utilizing existing cost estimating relationships (CER's) for each of the components considered, and 3) the summation of equations for respective system components to establish the total system cost estimation. CER's developed in Contract NAS9-9018 were used, with appropriate modifications, to estimate the cost of the components considered. For example, a gaseous storage tank CER was used for the gas accumulator and the LiOH canister CER was used for the silica gel, molecular sieve, and regenerable solid desiccant canisters. The costs of small components such as manual and sequence valves were made on a weight basis. An assembly factor for integrating the components was also used.

Definition of the cost element structure and the application of the CER's are given in the following paragraphs.

COST ELEMENT STRUCTURE:

The cost element structure provides visibility of the total project expenditures and permits identification of the significant project costs. Expenditures are divided into nonrecurring and recurring:

Nonrecurring - The nonrecurring expenditures for each life support subsystem are segragated into Prime Contractor and Major Subcontractor efforts. The Prime Contractor effort involves specification, coordination and integration of the system into the spacecraft. The Major Subcontractor effort is divided into Design and Development, AGE, Program Management and System Engineering, Test Operations and Hardware. The Design and Development costs are segregated into major subsystems.

Recurring - The recurring expenditures are divided into the Prime
Contractor and Major Subcontractor costs. The Prime Contractor
efforts involve primarily the incorporation of the life support
systems into the spacecraft. The Major Subcontractor costs are
broken into Sustaining Engineering, Tooling and System Production.
The System Production expenditures are segragated into subsystems
and these are in turn segregated into components.

Table 1 presents a typical breakdown of the life support system expenditures,
as encountered in the Gemini Program, divided in the respective non-recurring
and recurring items. The major nonrecurring costs are those related to
Design, AGE, and Prime Contractor's specification and procurement efforts.
The major recurring cost item is that of flight hardware production.

EFFECT OF INFLATION ON COST ESTIMATES:

A major inherent feature of the methodology which is highly critical to the
accuracy of the results obtained pertains to inflation and economic escala-
tion. Since computed CER's are based on specific year dollars, they must
be inflated to the proper year in order to obtain realistic future program
values. Due to the lack of a specific aerospace price index, the yearly
d ollar value adopted in this report was considered to correspond to the
Consumer Price Index. Figure 1 shows the Consumer Price Index based on
data published by the U. S. Bureau of Statistics.

TABLE I – REPRESENTATIVE LIFE SUPPORT SYSTEM EXPENDITURE BREAKDOWN

| NON-RECURRING	%	RECURRING	%
Design	16.68	Flight Hardware Production	54.56
Subcontractor General & Administrative	8.62	Subcontractor G&A	9.22
Sbucontractor Fee	3.62	Subcontractor Fee	3.88
Program Management	1.24	Program Management	1.36
System Engineering	5.25	Sustaining Engineering	1.96
Development Test	3.44		
Qualification Test	2.54		
Reliability Test	4.09		
AGE	18.45		
Tooling	3.87	Sustaining Tooling	1.69
Non-accountable Test Hardware			
Specifications, Vendor Coordination and Procurement Expenses	13.62	Specifications, Vendor Coordination and Procurement Expenses	15.49
System Integration	8.36	System Integration	7.15
Prime's Testing	8.17	Minor Subcontracts	4.69
Minor Subcontracts	0.38		
TOTAL	100%		100%
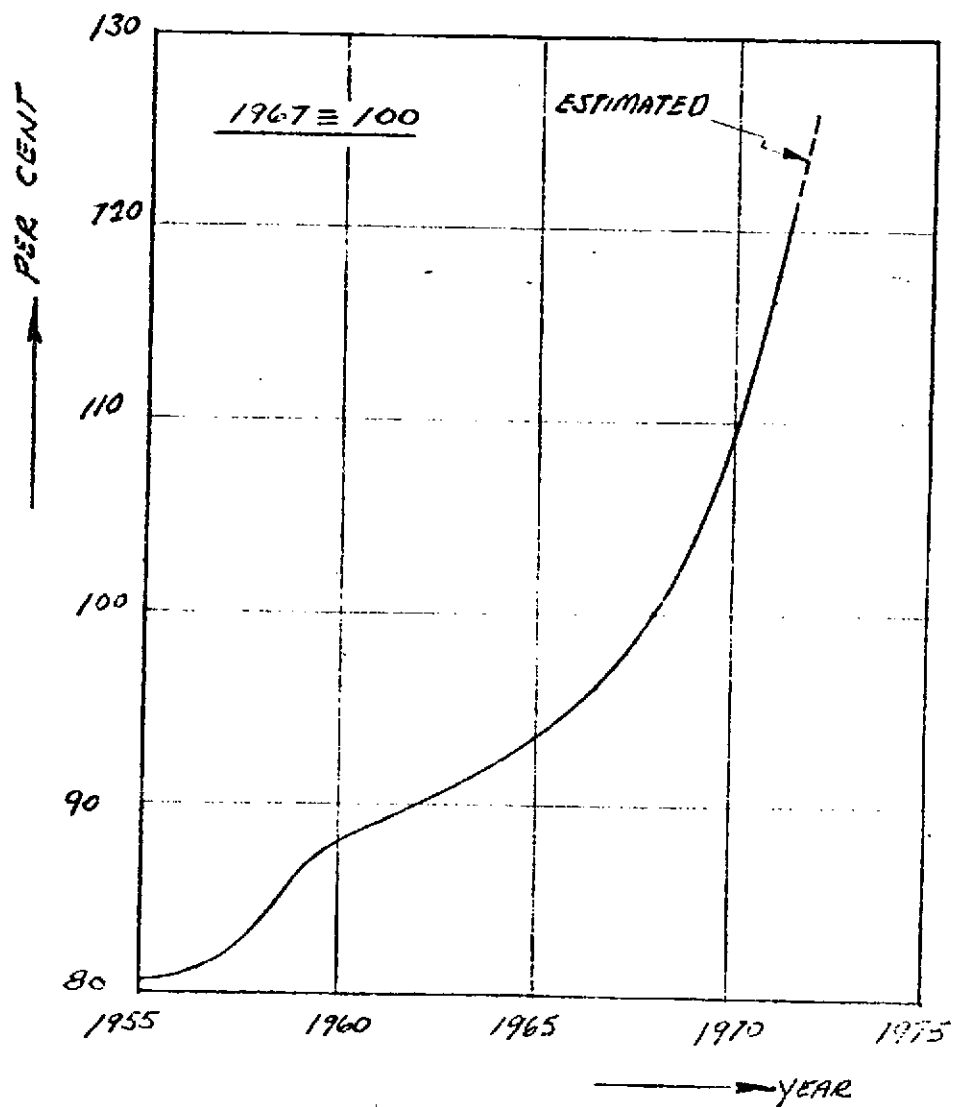
FIGURE 1 - Consumer Price Index
(Source: U. S. Bureau of Labor Statistics)

Section 3

ATMOSPHERE MONITORING SYSTEMS

The design of manned spacecraft life support systems for extended
duration requires the monitoring and removal of atmospheric contaminants
to insure a purified, breathable atmosphere. The system must cope with a
wide variety of compounds produced both metabolically and from the vehicle
systems. The presence of certain trace contaminants in closed space cabin
atmospheres can have very serious consequences, leading to loss of crew
efficiency, incapacitation; and even mission abort. Consideration of these
possibilities has lead to the definition of lists of critical contaminants,
development of monitoring procedures, and control of allowable materials to
prevent excessive off-gassing. Lists of contaminants which have been found
in closed manned chamber tests and manned space missions have been developed.
On extended missions, regenerable adsorption beds and catalytic oxidizers
have been proposed. The criteria developed and results of contaminant
measurements in closed-chamber tests of manned systems are applicable to
future manned space missions. Particularly, the Space Shuttle and associated
spacecraft must meet requirements for acceptable atmospheric contaminants
with cost-effective definitions of material limitations, to allow a variety
of payloads; of preflight checkout procedures to allow efficient turn-around
between missions; and of in-flight monitoring instrumentation. Table II lists and
summarizes the trace contaminants found in the NASA/MDAC 90-day test. This
table lists the major compounds which were tested for, the concentration
limits established by the NAS/NRC ad hoc committee, and the test findings.
Compounds, together with common alternate names, are listed by molecular
weight. With the exception of complex organic compounds, chemical formulas
are given. The lower contingency level values established by the ad hoc
committee are given, where applicable, in millimoles per 25 m^3, which is
essentially equivalent to ppm at sea level.

In selecting an instrument for gas analysis two major requirements must be
considered. The first is the capability to sense a large number of gases which

TABLE II

SPACE CABIN ATMOSPHERIC CONTAMINANTS

Mol. Wt.	Name	Alternate	Formula	NRC/UAS 90-day Level ppm (1) At Sea Level	Found in 90-day Test ppm (1) at Sea Level or F/NF				Possible Source
					Cabin	Sil Gel	Mol Sieve	Act Carbon	
16	Methane		CH$_4$	-	198	-	-	-	Metabolic Product
17	Ammonia		NH$_3$	75	2	-	-	-	Decomposition of urea
28	Carbon monoxide		CO	60(5)	18	-	-	-	Metabolic product
30	Formaldehyde		HCHO	0.1	NF(2)	-	-	-	Metabolic product
30	Nitric Oxide		NO		(3)				Decomposition of NH$_3$ in catalytic oxidizer
32	Methanol	Methyl alcohol	CH$_3$OH	-	F	-	-	-	Metabolic product
34	Hydrogen Sulfide		H$_2$S	-	NF	-	-	-	
46	Nitrogen Dioxide		NO$_2$	-	0.07(3)	-	-	-	Decomposition of NH$_3$ in catalytic oxidizer
46	Ethyl Alcohol	Ethanol	C$_2$H$_5$OH	-	1.0	-	-	-	Metabolic product
48	Ozone		O$_3$	-	NF	-	-	-	
58	2-Methyl Propane	Isobutane	(CH$_3$)$_3$CH	-	-	-	-	P	Metabolic product; solvent
58	2-Propanone	Acetone		-	1.6	P	F	P	
60	Ethyl Acetate	Acetic acid	CH$_3$CO$_2$H	10	NF	-	-	-	Pretest cleaning or solvents
60	2-Propanol	Isopropyl alcohol		-	F	-	-	-	
64	Sulfur dioxide		SO$_2$	-	NF	-	-	-	
71	Chlorine		Cl$_2$	-	NF	-	-	-	
72	2-Butanone	Ethyl methyl ketone	-	20	0.2	-	-	F	Pretest Cleaning or solvents
72	2-Methyl butane	Isopentane		-	-	-	-	P	
72	Pentane		CH$_3$(CH$_2$)$_3$CH$_3$	-	-	-	F	P	
74	2-Butanol	Butyl alcohol		10	P	F	F	P	
78	Benzene			-	-	F	-	P	Pretest cleaning or solvents
84	Cyclohexane			-	F	-	-	-	
85	Dichloromethane	Methylene chloride	CH$_2$Cl$_2$	25	P	F	F	-	
86	2,2-dimethyl butane	Neo-Hexane		-	F	-	-	-	
86	Hexane		CH$_3$(CH$_2$)$_4$CH$_3$	-	-	-	F	F	
86	2-Methyl butanone			20	NF	-	-	-	
88	Dioxane			10	NF	-	-	-	
92	Methyl benzene	Toluene		-	0.10	F	F	F	Pretest cleaning or solvents
97	1,1-Dichloroethene	Vinylidene chloride	CH$_2$:CCl$_2$	6(4)	NF	-	-	-	
98	1-Pentene			-	-	-	F	-	
99	1,2-dichloroethane	Ethylene chloride	Cl CH$_2$:CH$_2$Cl	-	0.17	F	F	F	Pretest cleaning or solvents

TABLE II (Continued)

SPACE CABIN ATMOSPHERIC CONTAMINANTS

Mol. Wt.	Name	Alternate	Formula	NRC/NAS 90-day Level ppm(1)	Found in 90-day Test ppm (1) at Sea Level or F/NF				Possible Source
					Cabin	Sil Gel	Mol. Sieve	Act. Carbon	
100	Heptone		$CH_3(CH_2)_5CH_3$	-	F	-	-	-	
100	4-Methyl-2 Pentanone	Isobutyl methyl ketone		-	-	F	F	-	
102	2-Ethyl-1-butanol			-	-	F	F	F	
106	1,2-Dimethyl benzene	O-xylene	C_8H_{10}	-	NF	-	F	-	
106	1,3-Dimethyl benzene	M-xylene	C_8H_{10}	-	F	-	-	-	
106	1,4-Dimethyl benzene	P-xylene	C_8H_{10}	-	F	F	-	-	
114	Octane		$CH_3(CH_2)_6CH_3$	-	-	F	F	-	
119	Trichloromethane	Chloroform	$CH\ Cl_3$	5	P	-	-	-	
129	Dichloroacetylene		Cl_2CHCO_2H	tr(4)	NF	-	-	-	
131	Trichloroethene	Trichloroethylene	$ClCH:CCl_2$	10	NF	-	-	-	
154	Tetrachloromethane	Carbon tetrachloride	CCl_4	-	-	-	F	F	Pretest cleaning or solvents
167	Acetic acid, nitrile	Acetonitrile		-	-	F	-	F	
187	Trichlorotrifl-roroethane	Freon 113	Cl_3CCF_3		8.0	F	F	F	Pretest cleaning or solvents
187	1,1,2-Trichloro-1,2,2-Trifluoroethane		$Cl_2CFC\ ClF_2$	1000	NF	-	-	-	

NOTES: (1) Units are actually millimoles per 25 cu meters which is equivalent to parts per million at sea level pressure.

(2) Measurement sensitivity may not have been adequate to detect formaldehyde at stated level (0.1 millimoles per 25 m^3)

(3) Total oxides of nitrogen were read, indicated here under NO_2.

(4) These values established by verbal request of ad hoc committee.

(5) The value for carbon monoxide limit stated in Reference 1 (15 millimoles per 25 m^3) was revised per verbal request of the adhoc committee to 60 millimoles per 25 m^3 for the 90-day test.

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are most commonly found in the atmosphere, and the second is the growth capability of the instrument to enable detection of additional compounds that may be specified at a later date, as well as to provide information to identify unexpected contaminants. Gas analysis equipment with such capabilities fall in three distinct categories: 1) Absorption Spectroscopy, 2) Mass Spectrometry, and 3) Gas Chromatography. Instruments utilizing absorption spectroscopy are characterized by the use of the selective absorption bands of the various gases. Absorption Spectroscopy Systems include infrared, molecular resonance and microwave spectrometry techniques. Wide use of these systems is being made made for the detection of specific components that have distinctive absorption bands. Infrared CO_2 detector which utilizes the absorption of CO_2 at 4.3 microns is an example of this type of units. However, a serious disadvantage of infrared devices is posed by some gases masking the absorption peaks of other gases. For example, CO cannot normally be detected by this technique since it would be masked by the presence of N_2O which displays an absorption band at essentially the same wave length.

The disadvantages cited for absorption spectroscopy are not shared by the other two major analysis methods: Mass Spectrometry and Gas Chromatography. Mass Spectrometers have long been used in the petroleum and chemical industries. Gas Chromatography also has found widespread use in process industries. Both techniques have been regarded as reliable means of analysis. Their use in spacecraft applications,previously in unmanned vehicles and currently as an experiment in the Skylab Program, has been mainly involved with miniaturizing the units to reduce their size and power requirements. Subsequently, the number of contaminants monitored by either a Mass Spectrometer or a Gas Chromatograph has been limited to few essential gases. For example, the Perkin-Elmer Company developed a four-gas Mass Spectrometer, sensing O_2, N_2, CO_2 and water vapor. Other units have been since developed with capabilities to sense six or seven gases. A new unit is now under development which is said would be capable of monitoring up to forty trace contaminant gases. The new unit will be a scan type Mass Spectrometer and will not be larger in size than the current

4- to 7-gas Mass Spectrometers. The comparative characteristics of the two systems considered, Mass Spectrometers and Gas Chromatograph, are given in Table III which also presents the physical differences, operational characteristics and status of each system.

TABLE III. - COMPARISON OF ATMOSPHERE MONITORING SYSTEMS

SYSTEM CHARACTERISTICS	MASS SPECTROMETER	GAS CHROMATOGRAPH
Number of monitored gases Monitored species, typical	4, 6 or 7 H_2, CO_2, N_2, H_2O, F-11, F-12, F-114, and total contaminants with m/e between 50 and 120	23 gases, with two columns. H_2, O_2, N_2, CH_4, CO, CO_2, H_2O and number of trace contaminants.
Concentration Range	0.5 to 50 PPM	10 PPM to 100% Full Scale
Accuracy	0.5 PPM: $\pm$ 100% 5 PPM: $\pm$ 20% 50 PPM: $\pm$ 10%	3%
Warm-up Time Operating Life	30 Minutes 60 days continuous without filament failure	60 Minutes 180 days
Volume	1000 In^3	400 In^3
Weight	15 Lbs	10 Lbs
Power	25 Watts	10 Watts
System Operation	1. Sample ionized into charged particles with varying m/e ratios. 2. Magnet used to separate particles with specific m/3 ratios.	1. Sample, in a carrier gas, passed through a packed column. 2. Preferential absorption of components of sample causes different rates of elution. 3. Detector-amplifier produces signals proportional to concentration of concentration of components in sample.
System Status/Availability	1. Flight prototypes developed for 4, 6 and seven gases. 2. Six-gas unit to be used in Skylab experiment.	1. Flight units developed only for unmanned flights such as one for Surveyer to analyze

TABLE III. - COMPARISON OF ATMOSPHERE MONITORING SYSTEMS (Continued)

SYSTEM CHARACTERISTICS	MASS SPECTROMETER	GAS CHROMATOGRAPH
	3. Six-gas Mass Spectrometer successfully tested in NASA/MDAC 90-Day Test. Unit also actuated cabin two-gas controller.	lunar soil.
		2. A Gas Chromatograph/Mass Spectrometer combination is currently under development for Viking Program.
	4. Forty-gas trace contaminants Mass Spectrometer currently under development. Low-Fidelity prototype expected in one year.	3. A Low-Fidelity prototype to monitor cabin trace contaminants was developed by NASA/MELPAR, but not used. Renewed development of a flight prototype similar to the NASA/MELPAR unit is required
Development Problems	None Anticipated	

COST ESTIMATING OF ATMOSPHERIC MONITORING SYSTEMS

4.1 MASS SPECTROMETER:

Process Description:

The principle of Mass Spectrometry involves the ionization of a sample into charged particles which are separated into their characteristic mass to charge ratios and then detected. Mass Spectrometers currently under development are of the magnetic field type shown in Figure 2, in which the particles are accelerated by an electric field. Each mass to charge ratio is accelerated to a characteristic velocity dependent upon the accelerating voltage. They then pass through a magnetic field where the degree of deflection is a function of the mass to charge ratio of the particles. The field separates the ions into beams, each of a different mass to charge ratio. By varying the accelerating voltage the resultant beams are successively directed through a resolving slit and onto a collector. The resultant current is amplified and provides a measure of the number of ions at each mass to charge ratio.

Current Mass Spectrometer Systems include a number of small 90° magnetic sector type units which provide four, six or seven simultaneous and linear type voltages that are proportional to the partial prrssures of a corresponding number of gases. Atmospheric gases measured by these Mass Spectrometers include H_2, CO_2, O_2, N_2, N_2O, F-11, F-12, F-114 and total contaminants. The total contaminants include constituents with mass-to-charge ratios of 50 to 120. For the purpose of this study, a six-change Mass Spectrometer will be considered. Modifications to existing Mass Spectrometers will then include the collector configuration and expected repackaging for the required application.

A basic schematic block diagram of the system is shown in Figure 3 which may be conveniently divided into two subsystems; the analyzer subsystem and the electronics subsystem. The analyzer subsystem consists of that part of the device which admits the gas to be sampled to the system, ionizes the sample to form the charged particles which are then resolved in the magnetic sector, and maintains the internal vacuum necessary for operation of the instrument. The electronics subsystem consists of the various circuits required to supply voltages and currents for the operation of the analyzer as well as

SAMPLE INLET

ANODE

ION SOURCE

FILAMENT

ELECTRON BEAM

ION FOCUSING LENSES

OBJECT SLIT

ION BEAM

MASS SEPARATION
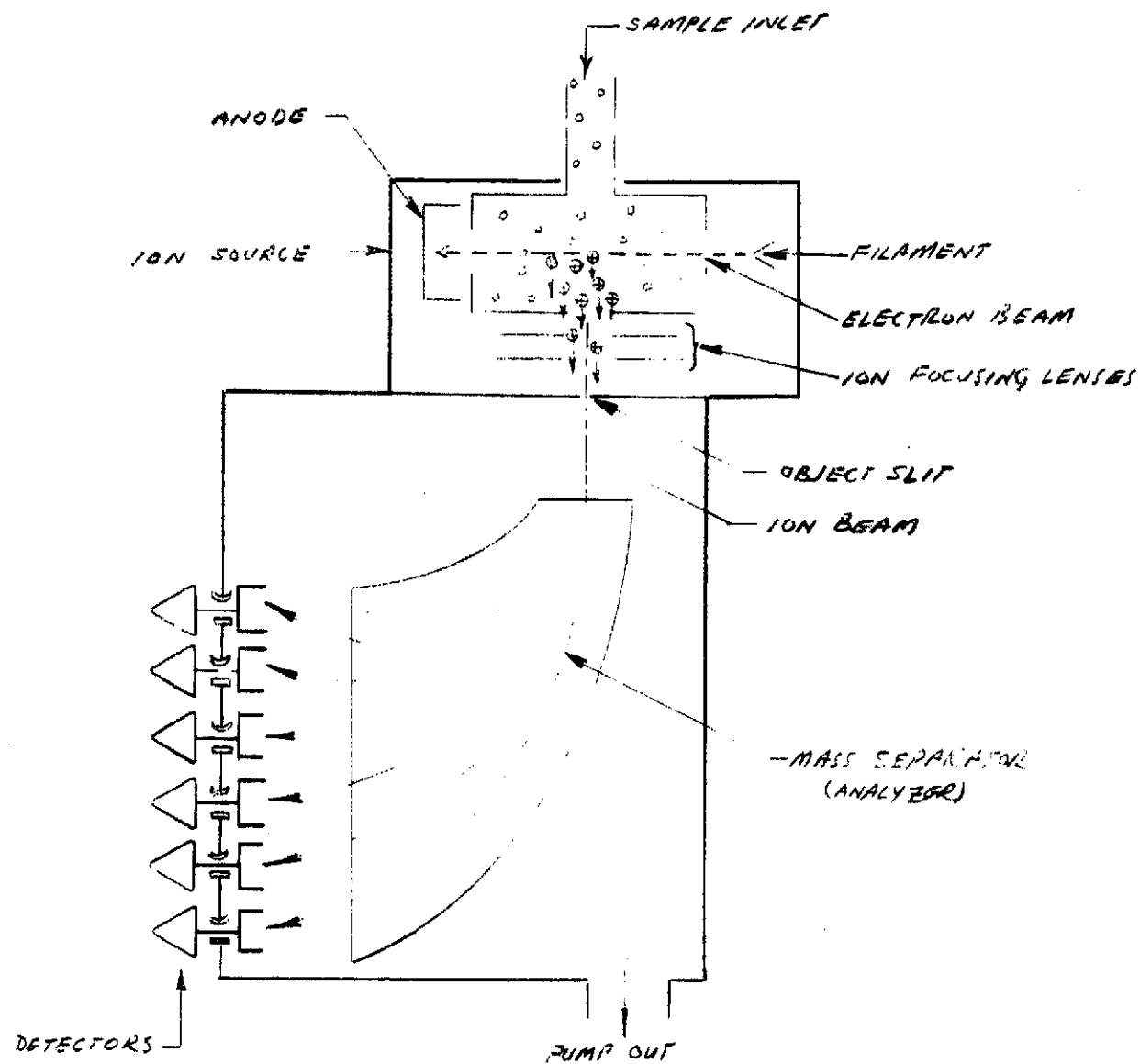(ANALYZER)

DETECTORS

PUMP OUT
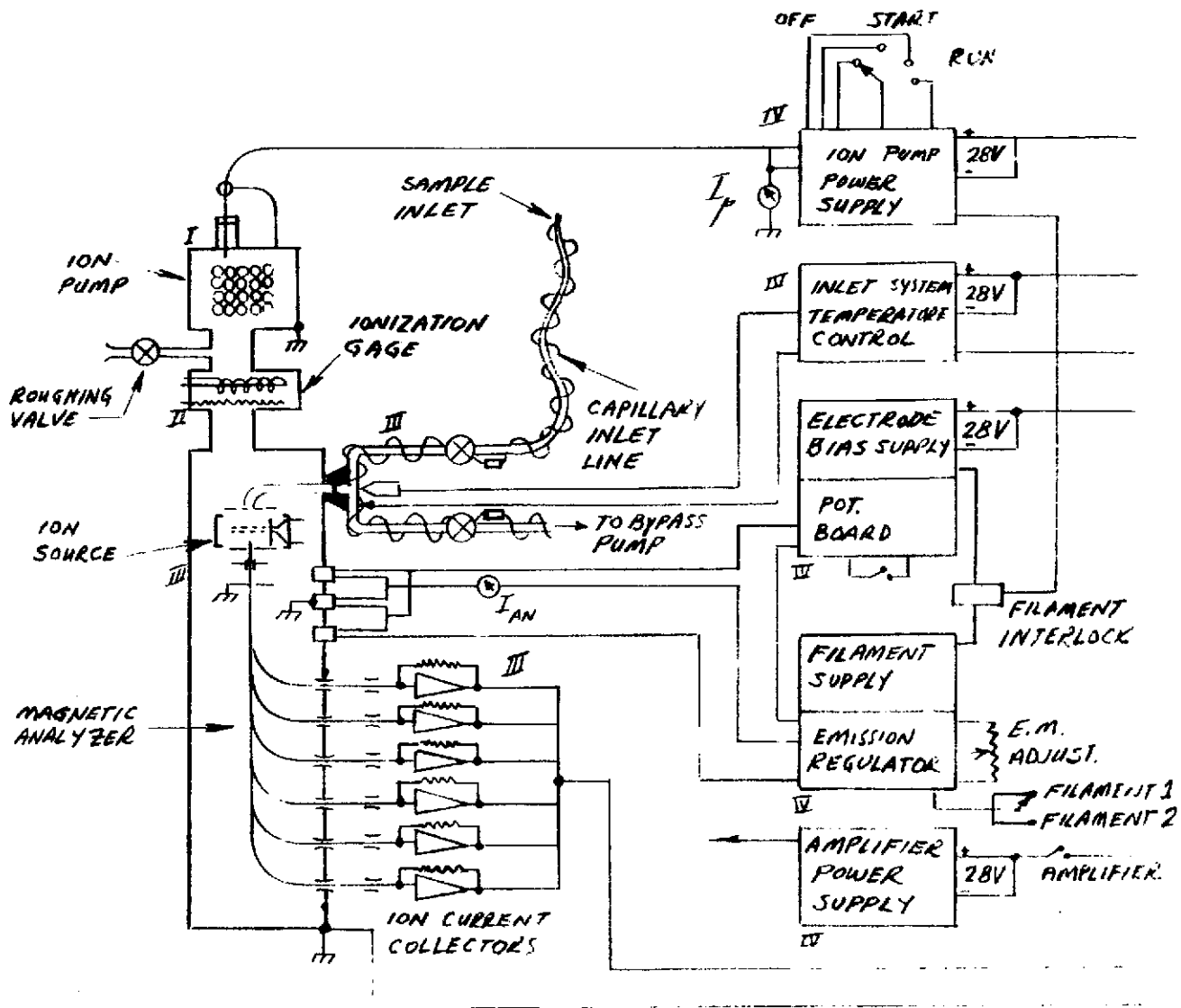
FIGURE 2.   MAGNETIC FIELD TYPE MASS SPECTROMETER

FIGURE 3. MASS SPECTROMETER SYSTEM SCHEMATIC

for the amplification of the ion current outputs. The two subsystems are housed in a system enclosure with the necessary inputs and outputs. A more detailed description of the system is given in the following paragraphs.

The inlet system consists of a viscous-flow capillary line that samples the atmosphere at one standard atmosphere and reduces the pressure to seven torr by means of the pressure drop in the flow channel. At the point where the nominal pressure is seven torr, the flow is sampled by an orifice that provides a molecular flow into the ion source. The capillary line is approximately six feet in length, which allows some flexibility in the location of the sampling point relative to the mass spectrometer. The ion source, which is contained in the analyzer housing is a dual filament, nonmagnetic type that employs two electron guns that are mounted in an orthogonal configuration. The filaments are 0.003 inch diameter tungsten-rhenium wires. The ion source has a limited gas conductance to isolate the ionizing region from undesirable variations in the filament and ion pump regions which can cause variations in the sensitivity. The ions exit from the ion source at the exit slit and are injected into the magnetic sector region of the analyzer. This is a 90-degree magnetic sector which disperses the ion beam according to the mass-to-charge ratios of the ions while correcting to first order for the angular spread of the ion beam. Six ion current collectors are located on the focal plane of the analyzer and receive the ions from six atmospheric constituents. The positions of the collectors are adjustable to facilitate the simultaneous collection of the six species. The magnetic field of 4000 gauss is supplied by a permanent magnet.

A vacuum envelop houses the ion source and the magnetic sector. It is typically a thin walled stainless steel housing which is electrically accessible through feedthroughs. The electronics circuits necessary for the operation of the analyzer include the following:

  a. An electrode bias supply which provides voltages for the ion source focusing electrodes.

b. A filament supply and emission regulator for the control of the ionizing electron beam.

c. The six electrometer amplifiers for amplification of the ion current signals.

d. A ±10 volt power supply for the B+ and B- voltages that operate the electrometers.

Multiple pin headers introduce voltages from the ion source electronics and feed them to the filaments and to the various focusing electrodes, while single pin feedthroughs transmit the ion currents from the ion current collectors to electrometer amplifiers which amplify the small ion currents to the levels required for output.

Each of the collected ion currents is amplified to the required output level by an all solid-state electrometer amplifier. Each amplifier is set for the sensitivity commensurate with the expected sample range of that atmospheric component. These amplifiers have a high input impedence and utilize 100% current feedback to obtain an output which is essentially independent of any active devices. The output voltage is equal to the input current multiplied by the feedback resistance.

In addition to the ion current amplifiers the sensor system support electronics subsystem consists of three modules which provide the electronic functions necessary for the operation of the analyzer. First, there is a filament supply and emission regulator which supplies an AC voltage to the filament. This is a closed loop control system which senses the ionizing current that is collected at the anode of the ion source and uses this as feedback current to control the filament power so that the ionizing current remains constant. System considerations also require that this module be floated above ground at the anode potential. An inverter is used for this and its pulse width modulated output drives the filament.

The electrode bias supply provides the voltages to the various focusing electrodes in the ion source. It consists of a single inverter with a multiple winding output. Series voltage regulators operate off of two of the rectified outputs and these are used to compensate for variations in two of the other outputs. The result is three stacked high voltage outputs, two that are regulated and one that is unregulated. These outputs are loaded by a resistance voltage divider network with potentiometers which are cabled to the ion source headers.

The detector power supply consists of a single free running inverter which drives regulators that supply +10 and -10 volts to the detectors.

System Performance And Characteristics:

The physical, performance and interface characteristics of the Mass Spectrometer System are as follows:

Monitored Species	Six gases with m/e ratios between 2 and 120. Typical gases are H_2, CO_2, N_2, H_2O, F-11, F-12, F-114 and total contaminants with m/e between 50 and 120
Concentrations Range	0.5 to 50 PPM
Accuracy	0.5 PPM: $\pm100\%$ 5 PPM: $\pm20\%$ 50 PPM: $\pm10\%$
Sample Gas Loss	250 torr cc/sec at one atmosphere.
Maximum Operating Pressure	800 torr with 1 atmosphere capillary.
Ion Source Pressure	The ion source can maintain linear operation up to a pressure of 2×10^{-4} torr.
Differential Pressure	100:1 (ion source pressure to analyzer pressure ratio).
Outputs	Six simultaneous, linear 0 to -5 volts.

Dynamic Range	200 torr for O_2, 0.1 to 50 torr for H_2O, CO_2, H_2, Freons, THC, or total contaminants.
Power	25 watts
Weight	15 pounds
Volume	0.6 ft.^{3}
Operating Temperature Range	40 to 90°F
Warm Up	30 minutes for full temperature stabilization.
Expected Operating Life	Sixty days of continuous operation without filament failure.

Cost Estimating Relationships:

The Mass Spectrometer system components have been grouped in four groups, designated as I through IV, as shown in the system schematic, Figure 3. The recurring and non-recurring CER's presented in the following paragraphs are based on estimated January 1972 dollars. The consumer price index was used to adjust CER's developed and based on prior years dollar values.

Recurring CER's:

1. The Ion Pump:

    The Ion Pump used with the Mass Spectrometer is a special type unit which was found to be a good compromise between size and pumping power for the application. As the size of the pump is not expected to vary appreciably with spacecraft size, mission duration or the number of species expected to be monitored, the currently used unit will be considered applicable to other size Mass Spectrometers. The said unit is a flight type pump with a capacity of 4 liters/second. The ion pump CER to be represented by the following non-variable relation:

    Ion pump fabrication cost = 4000   Dollars

2. Ionization Gage:

The ionization gage, added in the tube that connects the analyzer to the ion pump, is also considered as a special non-variable size item which, similar to the ion pump, has a relatively fixed cost. A tube is welded into the ionization gage chamber for rough pumping the analyzer, with a valve added to the line to close it off after rough pumping. The cost of the ionization gage, including the valve is given as follows:

$$\text{Ionization gage fabrication cost} = 2500 \quad \text{Dollars}$$

3. Analizer Assembly:

The CER for the analyzer assembly, comprised of the sample inlet system, ion source analyzer magnet and ion collector assembly is given as follows:

$$\text{Analyzer assembly fabrication cost} \quad C$$
$$= 4000 + 500 \, N_c \qquad \qquad \text{Dollars}$$

where N_c = number of ion collector per assembly.
Substituting the value of $N_c = 4$ in the CER yields:

$$C = 400 + 2000 = 6000 \qquad \text{Dollars}$$

4. Electronic Equipment:

The CER for the fabrication costs of the electronic equipment, mounted on printed circuit boards and including packaging and panel construction, has been based on current similar electronic hardware manufacturing costs and is given as follows:

$$\text{Electronic equipment fabrication cost} = 150 \, N_B + 500 \qquad \text{Dollars}$$

where, N_B = number of printed circuit boards per assembly. The Mass Spectrometer System was found to require the following printed circuit boards: 1) amplifier power supply, 2) inlet system temperature control 3) filament supply, 4) electrode bias supply , and

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5) ion pump power supply. Substituting the value for $N_\delta = 5$
in the above CER yields the following:

$$C = 150 \times 5 + 500 = 1250 \qquad \text{Dollars}$$

Integrated Mass Spectrometer System's Recurring CER:

The integration costs of components and assemblies into the Mass
Spectrometer System are obtained by utilizing the system's recurring CER
as defined in previous volumes of this report. Applying the said CER, then

First unit cost $C_F = 1.833 \times 1.1 \times (4000 + 2500 + 6000 + 1250)$

$$C_F = 27,724 \qquad \text{Dollars}$$

and assuming the production of two flight-type units, one for flight
and one for back-up, then the total hardware cost is given by:

$$C_T = 27,724 \times (2)^{1-0.1047} = 51,428 \quad \text{Dollars}$$

Integrated Mass Spectrometer System's Non-Recurring Cost:

Non-recurring CER's have been developed for engineering design only.
Other non-recurring cost estimates are based on the cost breakdown ratios
utilized in the case of the molecular sieves system which have been based on
actual cost data collected in NAS9-9018 study. A system design CER has been
developed for the Mass Spectrometer which combines the effects of both mechanical
and electronic system designs. The analysis of a number of cost influencing
parameters indicated that mechanical engineering design CER is mainly a function
of the number of component types (N) in the system. For electronic system
design the cost is a function of the number of printed circuit boards involved.
The combined design CER is thus given by the following relation:

System design cost $C = 34,935\, N + 3000 N_8$ \qquad Dollars

where

N = number of component types designed, however since all
components have been already designed except for modification of
of collector and repackaging, N is considered $=$ 1, and

N_B = number of printed circuit boards = 5. Substituting the
values of variables in the CER yields the following:

$$C = 34,935 + 3000 \times 5 = 49,935 \qquad \text{Dollars}$$

Values of other non-recurring cost items are listed in Talbe IV, which also
shows the breakdown of recurring cost items based on the production of two
flight hardware units. All cost figures are in estimated January 1972 dollars.

4.2 GAS CHROMATOGRAPH

The gas chromatograph consists of basically three elements: a sample
device, a chromatograph column assembly which physically separates the sample
constituents, and a detector-amplifier which produces an electrical signal
whose magnitude is proportional to the concentration of each component in the
sample. The chromatograph column normally consists of a length of coiled
tubing filled with a solid support medium which preferentially adsorbs the
individual components of the sample, causing them to pass through the column
at different rates of speed by a continuous flow of carrier gas. Some columns
consist of adsorption materials such as Silica Gel, Alumina, or Molecular
Sieve and other types of columns consist of a solid support, usually crushed
firebrick or Teflon, upon which has been placed a thin layer of a high boiling
point liquid. These partition liquid columns provide good separation for
organics and hydrocarbons, whereas the adsorption types are normally used for
separation of the fixed gases. The separation ability of the column is a
function of its length, the operating temperature, the flow rate of the carrier
gas and the type of material which it contains. The output signal from the
detector is a series of peaks, each peak representing a separate constituent.
This signal is normally amplified and displayed on a strip chart recorder,
or can be telemetered to Earth. By properly gating the output signal,
particular constituents such as oxygen, nitrogen and carbon dioxide can be
read out on individual indicators, thereby providing a continuous reading for
these key constituents within the capsule. As the individual components

TABLE IV – MASS SPECTROMETER SYSTEM COST BREAKDOWN

Non-Recurring		Recurring	
System Engineering Design	49,935	Flight Hardware Production (2 units)	28,059
Subcontractor General and Administrative	25,816	Subcontractor G&A	4,742
Subcontractor Fee	10,836	Subcontractor Fee	1,995
Program Management	3,745	Program Management	700
System Engineering	15,729	Sustaining Engineering	1,008
Development Test	10,281		
Qualification Test	7,590		
Reliability Test	12,234		
AGE	55,228		
Tooling	11,585	Sustaining Tooling	8,690
Non-accountable Test Hardware	4,994		
Specifications, Vendor Coordination and Procurement Expense	40,797	Specifications, Vendor Coordination and Procurement Expense	7,966
System Integration	25,017	System Integration	3,677
Prime's Testing	24,468		
Minor Subcontracts	1,149	Minor Subcontracts	2,412
Total	299,410		51,428

Total Mass Spectrometer System Cost = 299,410 + 51,428 - 250,838   Dollars

emerge from the column they pass through a detector cell which generates an electrical signal proportional to the concentration of the component. The Detector should be nonspecific and only be sensitive to the presence of the components in the carrier gas. Ionization detectors are now available which can provide sensitivity to virtually all eluted components in the ppm range or less.

A schematic diagram of a typical gas chromatograph, utilizing ionization detectors, is shown in Figure 4. The primary components of the gas chromatograph shown include a programmer, sample detector valve, an injection valve, a column selector valve, three partitioning columns, three cross-section ionization detectors and an amplifier assembly. The programmer controls the valve operations and sequentially selects the appropriate detector. The sample selector valve allows atmospheric samples to flow through the injection valve. The injector valve injects a known volume of sample into the column system at periodic intervals. The column selector valves are used to prevent the flow of helium and sample through two of the three columns when they are not in use.

The columns consists of: (1) Molecular sieve for permanent gas separation; (2) Carbowax-Amine coated teflon for the separation of NH_3, CO_2, H_2O, alcohols, and certain other organic compounds. The cross-section detector housing includes two chambers, one for each of the columns. The amplifier assembly automatically maintains the baseline at the zero level, except when a compound is eluted, and provides automatic attenuation of compound peaks present in concentrations greater than 50 to 100 ppm.

The gas chromatograph is supplied with helium gas from a helium storage reservoir through a regulator and pressure relief valves. The subsystem shown in Figure 2 includes a 90 cubic inch titanium helium storage tank designed to operate at a nominal 6000 psi working pressure. The 90 cubic inch sphere furnishes the carrier gas for continuous operation of the gas chromatograph for 15 days.

The analyzer assembly operates with ultrapure helium furnished to the gas circuit at 42 psia ($\pm$ 2% at 35° to 120°F). Helium enters the gas circuit at the injection valve assembly. It is sequentially controlled by the three valves of this assembly to "inject" the samples contained in any of three sample loops into a column.

From the injection assembly, either pure helium or the sample passes through a check valve to the upper valve assembly at the head of all chromatograph columns. The check valve prevents backflow in the column from diffusing the sample during injection, thereby ensuring sharper elution peaks.

Control of gases to each column and detector cavity is accomplished when the programmer energizes the valves at the top and bottom of a column. Three times during a typical 30-minute automatic cycle, two columns are operating simultaneously. In this case one column is completing an analysis while the other is being purged; however, only one detector is energized. Stable gas flow through the columns is critical for predictable chromatograms. Therefore, gas flow is maintained between 11 and 13 ml/minute for each column by individual meter valve adjustments following the upper valve assembly. For gas flow adjustment, flow through the columns and detector may be monitored through the test point connection below each detector vacity.

Gaseous components elute from each column into its respective detector chamber where they are sensed. The time of this sensing, as measured from the injection time, is determined by the specific adsorption characteristics of the gas with the column material and is therefore used to identify the gas. Actual sensing is accomplished by radioactive tritium foil ionizing the gas in a specific manner so that the ion current normally carried from the detector electrodes is increased. The resulting current is then amplified for electronic readout as a measure of the gas concentration.

Detectors operating pressure is 14.7 psia. A valve subassembly placed at the end of the gas circuit is used to automatically close in the event of operational power failure. Filters are also provided to remove dust particles. For the purpose of developing CER's, the gas chromatograph is construed to comprise the omponents shown in Figure 4. In addition, electronic components are also provided for the amplification of detector signals, zero compensation, amplifier attentuation and automatic programming. The gas chromatograph will thus consist of the following: 1) helium reservoir, 2) pressure regulator, 3) 8-way valve, 4) sample source valve, 5) solenoid and metering valves assembly, 6) columns and detector assemblies, 7) needle and 2-way solenoid valves, and 8) amplifiers and electronic equipment.

SYSTEM PERFORMANCE AND CHARACTERISTICS:

The gas chromatograph has the following physical and interface characteristics:

Columns (2)	Molecular sieve and teflon
Helium leakage, estimated	1.0 cc/hr
Operating life	180 days
Shelf life	44 years estimated (Incl. columns)
Volume	400 in^3
Power	10 watts maximum
Weight	12 lbs.
Accuracy	3% of full scale
Warm up time	one hour
Sample purge time	3 minutes
Sample pressure drop	2 inches of water

Cost Estimating Relationship:

The gas chromatograph system components have been grouped in four groups, designated as I through IV, as shown in the system schematic, Figure 4. The recurring and non-recurring CER's presented in the following paragraphs are based on estimated January 1972 dollars. The consumer price index was used to asjust CER's developed and based on prior year dollar values.
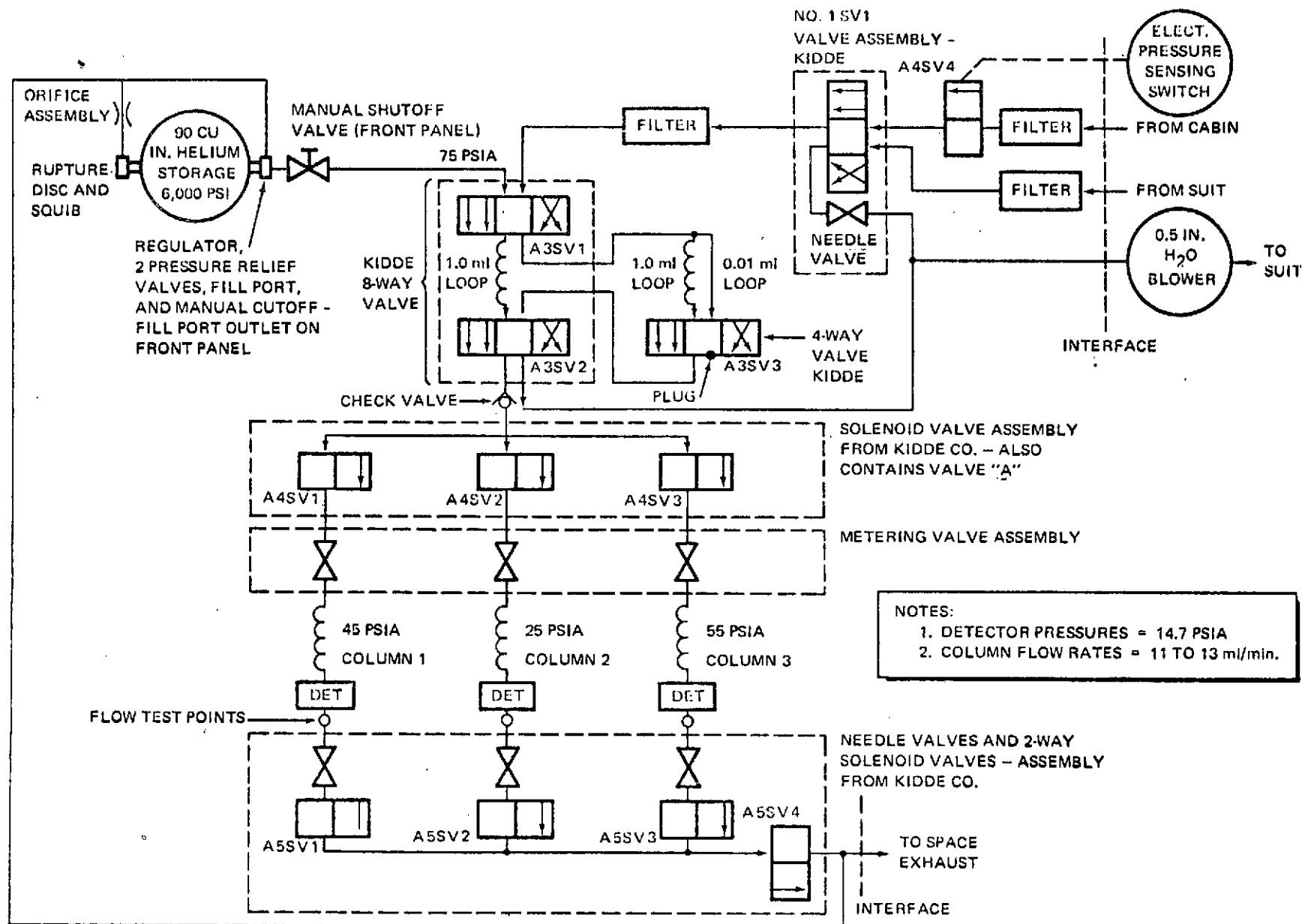
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FIGURE 4. GAS CHROMATOGRAPH SYSTEM SCHEMATIC

1. Helium Storage Tank:

The CER for the helium gas accumulator, based on a CER developed for high pressure gaseous containers, is given as follows:

Helium accumulator fabrication cost = $18{,}634\ V^{0.377} + 2959\ W_{oc}$ dollars,

where,

V = volume of accumulator = $0.1\ ft^3$ and

W_{oc} = weight of associated components = 1.2 lbs.

The associated components include a pressure regulator, two pressure relief valves, a fill port, an orifice and a manual shut-off valve..

Substituting the values of the variables in the above CER yields:

$$C = 18634 \times (0.1)^{0.377} + 2959 \times 1.2 = 11{,}380 \text{ dollars}$$

2. Gas Valve Assemblies:

The gas valve assemblies group include three filters, a sample source valve, a check valve, an injection valve assembly and a solenoid valve assembly. The CER for the gas valve assemblies is given by the following relationship:

Gas valve assembly fabrication cost $C = 2959 \times W_{GV}$ dollars,

where,

W_{GV} = gas valve assemblies weight = 2.8 lbs.

Substituting the valve of W_{GV} in the above CER yields

$$C = 2959 \times 2.8 = 8{,}285 \text{ dollars}$$

3. Columns and Detectors Assembly

The CER for the columns and detectors assmelby is based on CER's developed for adsorption beds and associated components and is given as follows:

Columns and detectors assembly fabrication cost $C = 5288 \, W_{col}^{0.267} \, Q^{0.89} +$

2959 W_{oc} dollars

where,

W_{col} = average column weight = 0.5 lbs,

Q = number of columns used = 2, and

W_{oc} = weight of associated components = 1.5 lbs.

Substituting the values of the above variables in the above CER yields the following:

$C = 5288 \times (0.5)^{0.267} \times (2)^{0.89} + 2959 \times 1.2 = 11,695$ dollars

4.   Amplifiers and Electronic Equipment:

The CER for the fabrication costs of the electronic equipment, mounted on printed circuit boards and including packaging and panel construction, has been based on current similar electronic hardware manufacturing costs and given as follows:

Amplifiers and electronic equipment fabrication cost $C = 150 \, N_B + 500$ dollars

where,

N_B = number of printed circuit boards per assembly. The gas chromatograph was found to require printed circuit boards for the following functions: 1) amplification of detector signal, 2) zero compensation, 3) amplifier attenuation, and 4) automatic programming. Substituting the value $N_B=4$ in the above CER yields the following:

$C = 150 \times 4 + 500 = 1,100$ dollars

Integrated Gas Chromatograph System's Recurring CER:

The integration costs of components and assemblies into the gas chromatograph system are obtained by utilizing the system's recurring CER as defined in previous volumes of this report. Applying the said CER, the first unit cost $C_F = 1.835 \times 1.1 \ (11,380 + 8285 + 11,695 + 1100)$ and assuming the production of two flight-type units, one for flight and one for back-up, then the total hardware cost is given by:

$$C_T = 65,602 \times (2)^{0.89} = 121,690 \text{ dollars}$$

Integrated Gas Chromatograph System's Non-Recurring Cost:

Non-recurring CER's have been developed for engineering design only. Other non-recurring cost estimates are based on the cost breakdown ratios utilized in the case of the molecular sieves system which have been based on actual cost data collected in NAS9-9018 study. A system design CER has been developed for the gas chromatograph, similar to that for the mass spectrometer, which combines the effects of both mechanical and electronic system designs. The analysis of a number of cost influencing parameters indicated that mechanical engineering design CER is mainly a function of the number of component types (N) in the system. For electronic system design the cost is a function of the number of printed circuit boards involved. The combined design CER is thus given by the following relation:

System design cost $C = 34,935 \ N + 3000N_B$ dollars

where,

N = number of major components types, considered equivalent to 3, and

N_B = number of printed circuit boards = 4, substituting the values of variables in the CER yields the following:

C = $2 \times 34,935 + 3000 \times 4 = 81,870$ dollars

Values of other non-recurring cost items are listed in Table V, which also shows the breakdown of recurring cost items based on the production of two flight hardware units. All cost figures are in estimated January 1972 dollars.

TABLE V – GAS CHROMATOGRAPH SYSTEM COST BREAKDOWN

Non-Recurring		Recurring	
System Engineering Design	81,870	Flight Hardware Production (2 units)	66,394
Subcontractor General and Administrative	42,326	Subcontractor G&A	11,220
Subcontractor Fee	17,766	Subcontractor Fee	4,722
Program Management	6,140	Program Management	1,655
System Engineering	25,789	Sustaining Engineering	2,385
Development Test	16,865		
Qualification Test	12,444		
Reliability Test	20,058		
AGE	90,548		
Tooling	18,994	Sustaining Tooling	2,056
Non-accountable Test Hardware	8,187		
Specifications, Vendor Coordination and Procurement Expense	66,888	Specifications, Vendor Coordination and Procurement Expense	18,850
System Integration	41,107	System Integration	8,701
Prime's Testing	40,116		
Minor Subcontracts	1,883	Minor Subcontracts	5,707
Total	490,890		121,690

Total Gas Chromatograph System Cost = 612,580 dollars

Section 5

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